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THE STRATEGY FOR THE SECOND PHASE OF AEROBRAKING MARS GLOBAL SURVEYOR

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On February 19, 1999, the Mars Global Surveyor (MGS) spacecraft was able to propulsively establish its mapping orbit. This event followed the completion of an extended orbit insertion phase that was characterized by two distinct periods of aerobraking. During the second period of aerobraking, called "Aerobraking Phase 2", the orbit period of the spacecraft was reduced from 11.6 hours to 2 hours in just over four months. This paper focuses on and describes the strategy developed for the second phase of aerobraking MGS. This description includes the baseline aerobraking flight profile and the key trajectory metrics that were monitored in order to successfully guide the spacecraft to its desired mapping orbit. Additionally, the planned aerobraking flight profile is compared to the actual aerobraking (trajectory) results.

INTRODUCTION

The Mars Global Surveyor (MGS) spacecraft was launched on November 7, 1996, and after a ten month interplanetary transit[1] was inserted into a highly elliptical capture orbit at Mars on September 12, 1997. Unlike other interplanetary missions, the MGS spacecraft was launched with a planned mission delta-V (ΔV) deficit of nearly 1250 m/s. To overcome this planned ΔV deficit, aerobraking techniques would be employed to establish the desired mapping orbit[2-6]. However, damage discovered to one of the spacecraft's two solar arrays after launch forced major revisions to the original aerobraking planning of the MGS mission[7-8]. In order to avoid a complete structural failure of the solar array, peak dynamic pressure levels for the spacecraft were established at a major spacecraft health review in November 1997. This was done following revisions made to solar array failure mode after the spacecraft exhibited anomalous behavior while aerobraking in early October 1997. These new peak dynamic pressure limits were roughly one-third of the originally planned mission design values. Incorporating the new dynamic

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pressure limitations into mission replanning efforts resulted in an "extended" orbit insertion phase for the mission. This extended orbit insertion phase was characterized by two distinct periods of aerobraking separated by several months in an intermediate orbit called the "Science Phasing Orbit" (SPO). The revised MGS mission timeline is shown in Figure 1. The MGS spacecraft is shown in its revised aerobraking configuration in Figure 2.

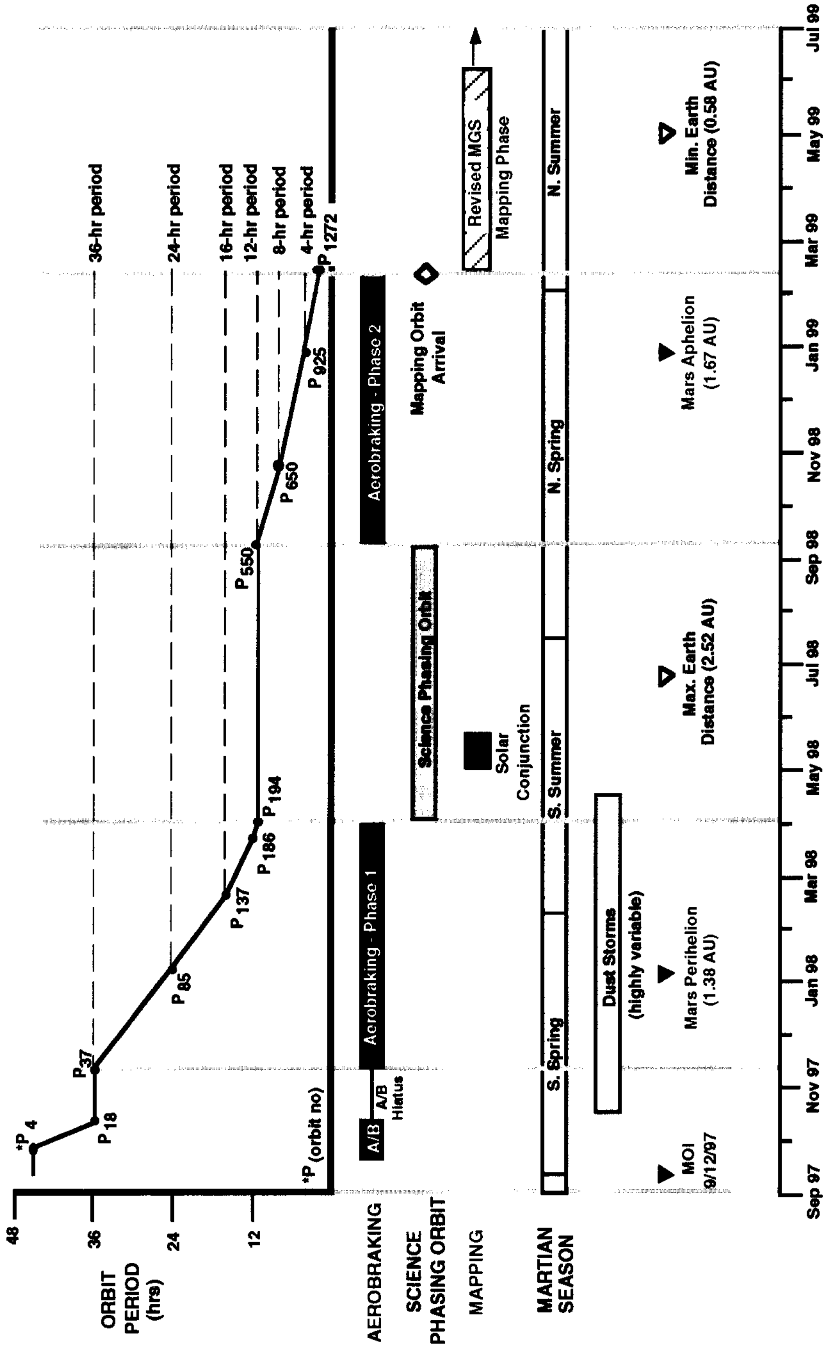

Figure 1 Revised MGS Mission Timeline

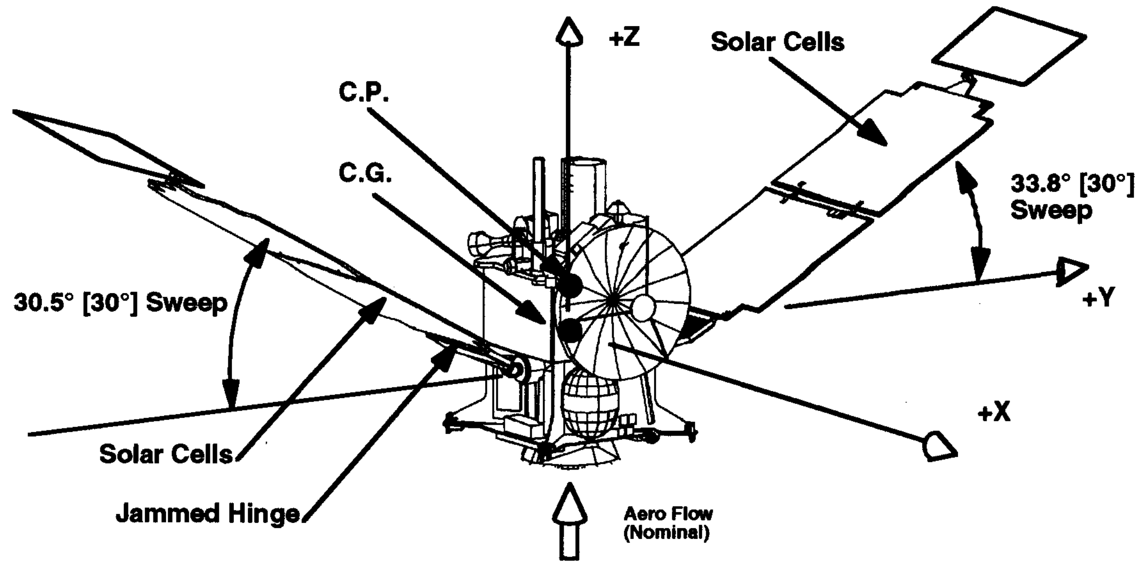

Figure 2 Revised MGS Spacecraft Aerobraking Configuration

On March 27, 1998, the first phase of aerobraking for MGS was completed with the establishment of the science phasing orbit. The SPO was necessitated by the need to temporarily suspend aerobraking operations because of solar conjunction and by the need to allow the descending node of the orbit to phase (regress) towards the local mean solar time (LMST) value desired for the MGS mapping orbit. The MGS mapping orbit can be characterized as a low altitude, near-circular, near-polar orbit that is Sun-synchronous with its descending equatorial crossing at 2:00 AM LMST. Because of science instrument requirements, the 2:00 AM LMST orientation is viewed as a key mapping orbit parameter that must be achieved within ±12 minutes LMST. Once in the desired mapping orbit, science data collection opportunities occur primarily along the ascending (dayside) pass of the orbit; in other words, the ascending node has a 2:00 PM LMST orientation. The achievement of this mapping orbit with its proper nodal orientation of 2:00 AM LMST (at its descending node) was the principal consideration in the development of the MGS extended orbit insertion phase. Other mapping orbits were considered post-launch after the damage to the solar array was detected but were discounted for various reasons. Because aerobraking operations were temporarily suspended during the time period of the SPO, the scientific investigators were afforded a special opportunity to collect data with their instruments over the northern polar region of Mars.

As the MGS spacecraft collected data during the SPO, plans were made for the spacecraft to perform a final phase of aerobraking. This paper describes and focuses on the strategy for this final phase of aerobraking called "Aerobraking Phase 2." This description includes the baseline aerobraking flight profile and the identification of the key trajectory metrics that were monitored in order to successfully "guide" the spacecraft to its desired mapping orbit. Additionally, the actual aerobraking trajectory that was flown is contrasted to the planned aerobraking flight profile.

AEROBRAKING PHASE 2 FLIGHT PROFILE DESIGN (June 1998): "Aerobraking Flight Profile to the 2:00 AM Mapping Orbit"

The Aerobraking Phase 2 flight profile was designed to accommodate the new dynamic pressure limits placed on the MGS spacecraft because of the damaged solar array. At the same time, the profile was designed to produce an orbit period reduction rate commensurate with achieving the 2:00 AM LMST mapping orbit. To ensure that sufficient dynamic pressure margins would be incorporated into the flight profile design, an early aerobraking start date was sought. After preliminary analysis, an aerobraking start date of September 14, 1998 was selected. This early start date would permit the aerobraking reference trajectory to be designed with an average dynamic pressure of less than 0.2 N/m^2.

Aerobraking Walk-in

To facilitate the flight profile development, the aerobraking trajectory is divided into three distinct sub-phases: a walk-in phase, a main phase, and a walk-out phase. During the walk-in phase initial contact with the atmosphere is established. Then through a series of small maneuvers the dynamic pressure levels are gradually increased to the desired main phase values. For the start of Aerobraking Phase 2, a series of three walk-in maneuvers were planned with the opportunity to perform more if necessary easily accommodated. Additionally, the first walk-in maneuver incorporated an orbit inclination correction of nearly 0.45 deg. This inclination correction is illustrated in Figure 3 and biased the orbit inclination at the start of Aerobraking Phase 2 with respect to the Sun-synchronous mapping orbit inclination. This bias was based on the average inclination variation that resulted from a series of end-to-end aerobraking trajectories. Because the orbit inclination

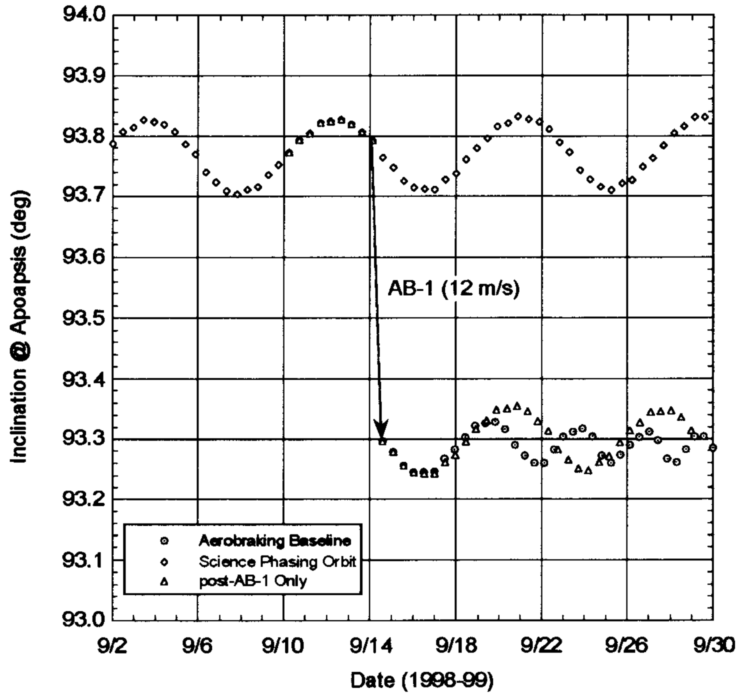

Figure 3 Inclination Bias
(Baseline Aerobraking Phase 2 Flight Profile - June 1998)

directly effects the rate of change of the node of the orbit, and the node with respect to the sun determines the current LMST, the inclination would be a parameter closely monitored during Aerobraking Phase 2.

Aerobraking Main Phase

During main phase, steady-state aerobraking conditions are established as the spacecraft is guided to dynamic pressure limits. During this time, control of the flight path of the spacecraft is achieved by performing small propulsive maneuvers at apoapsis. These small maneuvers are called aerobraking trim maneuvers (ABMs) and are used to maintain the spacecraft in a dynamic pressure corridor by raising and lowering periapsis. Because of damage to the array and the desire to provide margin against its potential failure, it was decided that the Aerobraking Phase 2 flight profile should be designed with dynamic pressure levels averaging less than 0.2 N/m^2. The selection of this 0.2 N/m^2 limit was due mostly to the experience gained during Aerobraking Phase 1. First, it was anticipated that the intrinsic atmospheric variability (orbit-to-orbit) would remain near the pre-launch estimate of 70% (2-sigma value). Programmatically, the desire was to maintain a 90% atmospheric density variation against the spacecraft redlines. Although very difficult to quantify because of the composite structure of the solar array yoke, it was generally accepted that dynamic pressure levels greater than 0.6 N/m^2 could be catastrophic to the spacecraft. Secondly, during Aerobraking Phase 1, it was observed that the actual orbit period reduction associated with a given level of dynamic pressure would not necessarily match the planned orbit period reduction of the baseline aerobraking trajectory. In order to achieve the same orbit period reduction as the planned aerobraking profile, the vehicle would have to be flown at higher dynamic pressure levels. The difference between the actual and the planned dynamic pressure values on some orbits would approach twenty percent. The phrase "aerobraking effectivity" was coined to describe this phenomena. Perhaps more appropriately, aerobraking effectivity reflects a current inability to precisely model the Martian atmosphere at high altitudes. Nevertheless, it was fully expected that the actual dynamic pressure values that the vehicle would experience during Aerobraking Phase 2 might be higher than those used in the profile design by about ten percent. As a result, the average dynamic pressure used in the flight profile design was biased to compensate for these aerobraking effectivity concerns.

In addition to applying a bias to the average dynamic pressure used in the main phase design, the aerobraking flight profile was "shaped" into two segments by employing a stepped dynamic pressure control strategy. For the first half of aerobraking main phase (from an 11.6-hour orbit period to a 5-hour orbit period), the vehicle would be flown at dynamic pressure levels expecting to average 0.18 N/m^2. For the second half of aerobraking main phase (from a 5-hour orbit period to a 2-hour orbit period) the vehicle would be flown at dynamic pressure levels expecting to average 0.13 N/m^2. This stepped dynamic pressure control strategy is illustrated in Figure 4 and was selected because it provides an additional measure of flight profile robustness. Namely, for a given level of dynamic pressure, a greater orbit period reduction rate is achieved in a longer period orbit than is achieved for that same level of dynamic pressure in a shorter period orbit. This is illustrated by comparing Figure 4, dynamic pressure control, to Figure 5, change in orbit period per orbit. For example, at the 9-hour orbit period mark, the orbit period reduction rate is about 2 minutes per orbit for a dynamic pressure value of about 0.2 N/m^2. In contrast, at the 6-hour orbit period mark, the orbit period reduction rate is about 1 minute per orbit for the same dynamic pressure value of about 0.2 N/m^2. Thus, for equivalent dynamic pressure values, the orbit period reduction rate is faster while the orbit period is

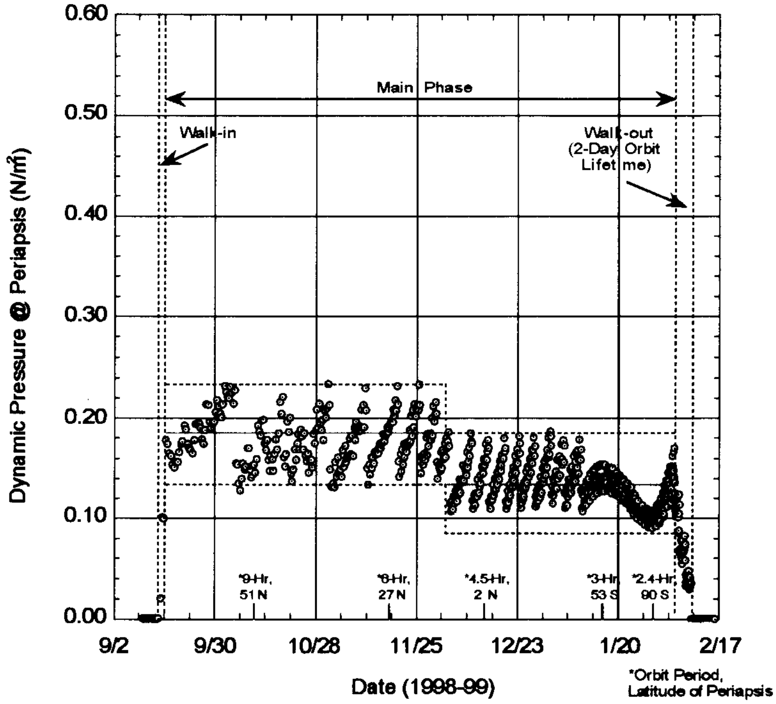

Figure 4 Dynamic Pressure
(Baseline Aerobraking Phase 2 Flight Profile - June 1998)

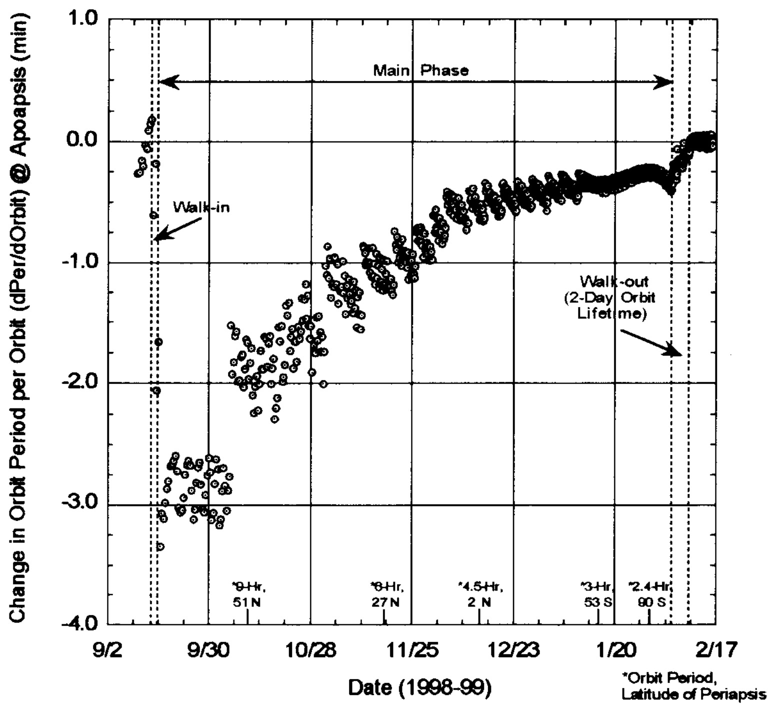

Figure 5 Change in Orbit Period Per Orbit
(Baseline Aerobraking Phase 2 Flight Profile - June 1998)

long. Flying higher dynamic pressure values early in the aerobraking profile helps to minimize the number of high level dynamic pressure drag passes needed at the end of aerobraking when the orbit period is short and thus reduces the number of high level dynamic pressure load (fatigue) cycles applied to the damaged solar array. Additionally, the lower dynamic pressure values at the end of aerobraking help to minimize periapsis timing (predict) errors. This in return reduces the number of daily drag pass sequence uplinks required by the spacecraft. Because the spacecraft would also have to aerobrake over the South Pole of Mars, it was highly desirable to fly lower dynamic pressure drag passes at the end of aerobraking because of the expected fall-off of the atmospheric density over the South Pole. Otherwise, the altitude of the spacecraft would have to be lowered to maintain the desired orbit period reduction rates.

Aerobraking Walk-out

Once the predicted orbit lifetime of the spacecraft reaches two days, the aerobraking walk-out phase begins. Orbit lifetime is defined as the time it takes the apoapsis altitude of the orbit to decay to an altitude of 300 km. During the walk-out phase, the periapsis altitude of the orbit is slowly increased as the two day orbit lifetime of the spacecraft is maintained. The two day orbit lifetime is a programmatic constraint aimed at preventing mission failure in the event control of the spacecraft is lost during the final few days of aerobraking, i.e. flight controllers have 48 hours to recover the vehicle before impact.

Aerobraking Profile Characteristics

The key trajectory parameters of the Aerobraking Phase 2 flight profile are shown in Figures 6 through 9. Each figure notes on it the different aerobraking sub-phases: walk-in, main phase, and walk-out. Collectively, this group of figures formed what came to be called the aerobraking "glide slope." Because the baseline aerobraking trajectory forms the basic guidance framework for the aerobraking trajectory control process, these figures would be constantly compared against the actual trajectory progress.

The orbit period reduction plan produced by the dynamic pressure control strategy of Figure 4 is shown in Figure 6. Note the distinct slope change in this figure associated with the drop of the dynamic pressure control at the 5-hour orbit period mark. The change in periapsis latitude is shown in Figure 7. Because of gravity field perturbations, periapsis would travel nearly 180 deg in latitude over the planet's surface -- from near the North Pole to over and past the South Pole. The local mean solar time of the descending node of the orbit as it regresses toward the desired 2:00 AM mapping orbit orientation is shown in Figure 8. The flattening of this plot near the start of the walk-out is indicative of the orbit becoming Sun-synchronous as the mapping orbit is established. Delays in aerobraking would force the LMST to values earlier in time that would be unacceptable for the mapping orbit. Figure 9 shows the expected orbit inclination variation as a function of orbit period. The general downward trend in the inclination is due to the effect of third body perturbations. Additionally, resonance effects are clearly visible at those orbit periods that are in resonance with the planet's rotation; e.g. the 8-hour orbit period. As was mentioned previously, the orbit inclination at the start of Aerobraking Phase 2 was biased with respect to the desired mapping orbit value to compensate for the expected magnitude of these perturbations. Additionally, because of the sun synchronous mapping orbit requirement, a small amount of propellant was allocated to correct orbit inclination errors once aerobraking had been completed.

It should be noted that the Aerobraking Phase 2 flight profile was developed using

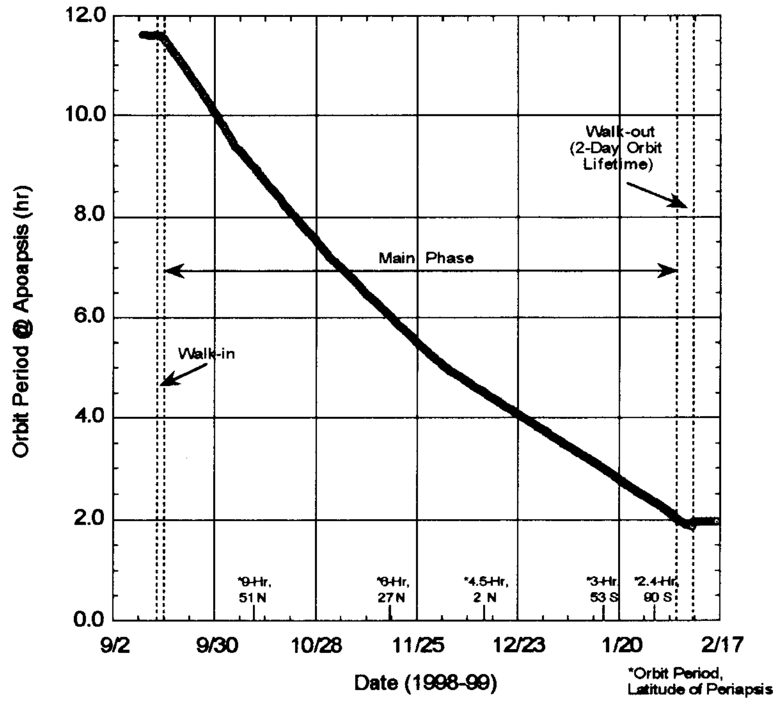

Figure 6 Orbit Period
(Baseline Aerobraking Phase 2 Flight Profile - June 1998)

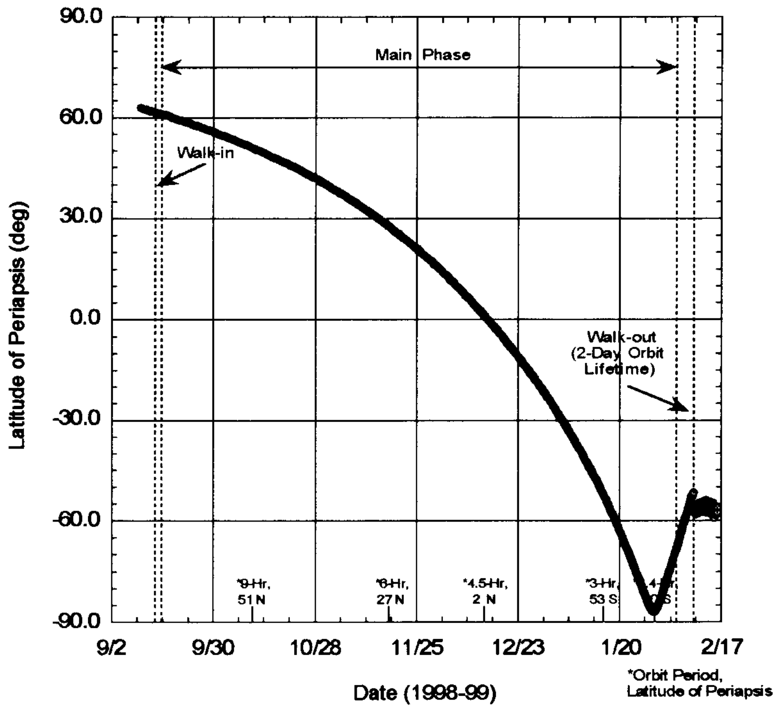

Figure 7 Latitude of Periapsis
(Baseline Aerobraking Phase 2 Flight Profile - June 1998)

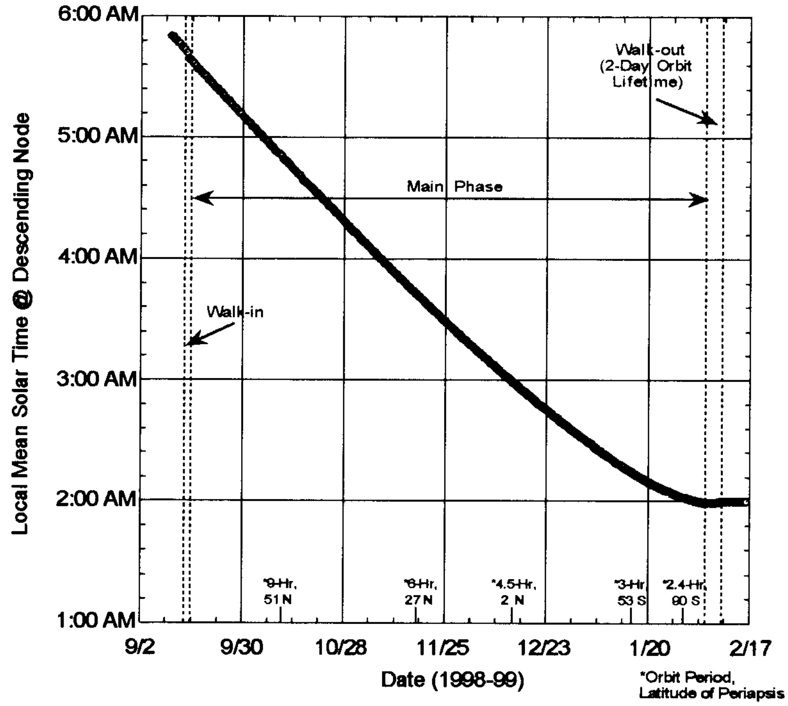

Figure 8 Local Mean Solar Time
(Baseline Aerobraking Phase 2 Flight Profile - June 1998)

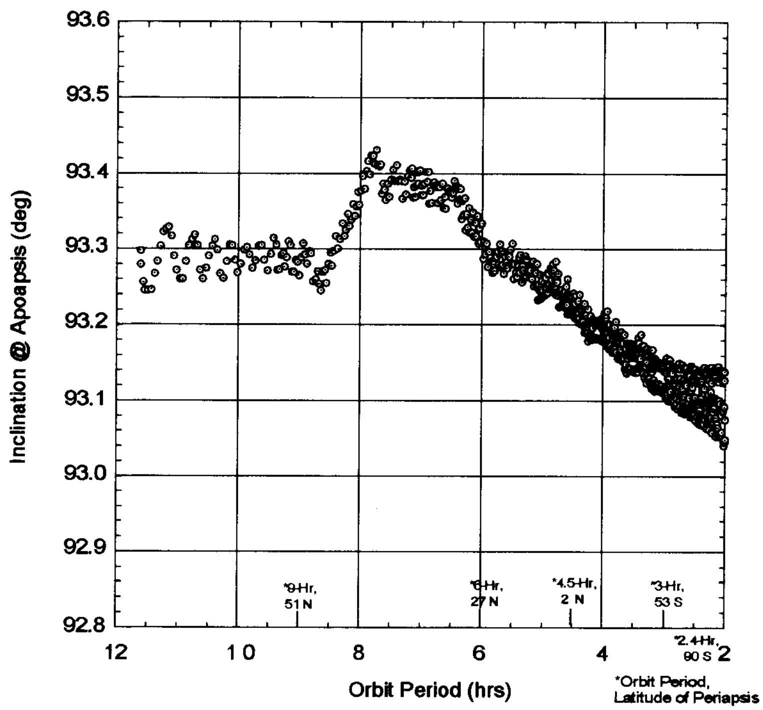

Figure 9 Orbit Inclination
(Baseline Aerobraking Phase 2 Flight Profile - June 1998)

the Mars-GRAM Atmospheric Model[9-10]. Although, MGS collected atmospheric data during Aerobraking Phase 1, significant revisions to the model were not available to support the Aerobraking Phase 2 profile design.

AEROBRAKING PHASE 2 FLIGHT PROFILE RESULTS

To achieve the proper nodal phasing of the 2:00 AM LMST Sun-synchronous mapping orbit, the orbit period reduction rate associated with the second phase of aerobraking must closely adhere to the planned aerobraking reference profile or glide slope. Large deviations from the planned profile would not be acceptable because the 2:00 AM mapping orbit condition would be jeopardized.

Aerobraking Walk-in

Although aerobraking was set to begin on September 14, 1998, spacecraft telecommunications anomalies and spacecraft sequencing problems triggered an initial aerobraking delay. This delay would last for a total of nine days as the cause of these anomalies was diagnosed and the plans for the aerobraking re-start updated. With the cause of the anomalies satisfactorily resolved, Aerobraking Phase 2 was initiated on September 23, 1998, with the execution of the first walk-in maneuver. At that time, the orbit had a period of 11.6 hours and a descending node orientation of 5:25 AM LMST. On September 25, 1998, after two more walk-in maneuvers were performed, the dynamic pressure values associated with the planned aerobraking main phase were achieved at a periapsis altitude of 118 km.

Aerobraking Main Phase

With the successful establishment of aerobraking main phase, flight operations began to focus on the recovery of the baseline glide slope. The delay in the start of aerobraking had created an orbit period deficit of nearly 65 minutes. To overcome this orbit period deficit, it was decided that the spacecraft would be flown at dynamic pressure levels slightly higher than the planned profile. This would increase the orbit period reduction rate and slowly eliminate the deficit. Further, it was decided that the orbit period deficit should be eliminated by December 2, 1998. In the planned trajectory, this corresponded to the 5-hour orbit period mark and the beginning of the second segment of the dynamic pressure control. To support the aerobraking trajectory control process, a special aerobraking trajectory was designed to "intercept" the Aerobraking Phase 2 flight profile on the desired target date. This intercept profile showed that the baseline orbit period reduction plan could be recovered by the December 2nd target date by increasing the dynamic pressure control twenty percent.

For the most part, main phase was characterized by steady-state aerobraking conditions as the spacecraft was guided to dynamic pressure limits. Figure 10 shows the actual Navigation determined dynamic pressure values at periapsis during Aerobraking Phase 2[11]. To "smooth" the apparent atmospheric variability, the dynamic pressure was averaged using a simple running mean technique. This running mean also served to trigger ABMs in support of the trajectory control process. Specifically, when the running mean fell outside of the limits of an established dynamic pressure corridor, ABMs would be performed to return the running mean to values within the corridor. These dynamic pressure corridor limits were reviewed and adjusted each week based on the actual orbit period reduction rates achieved.

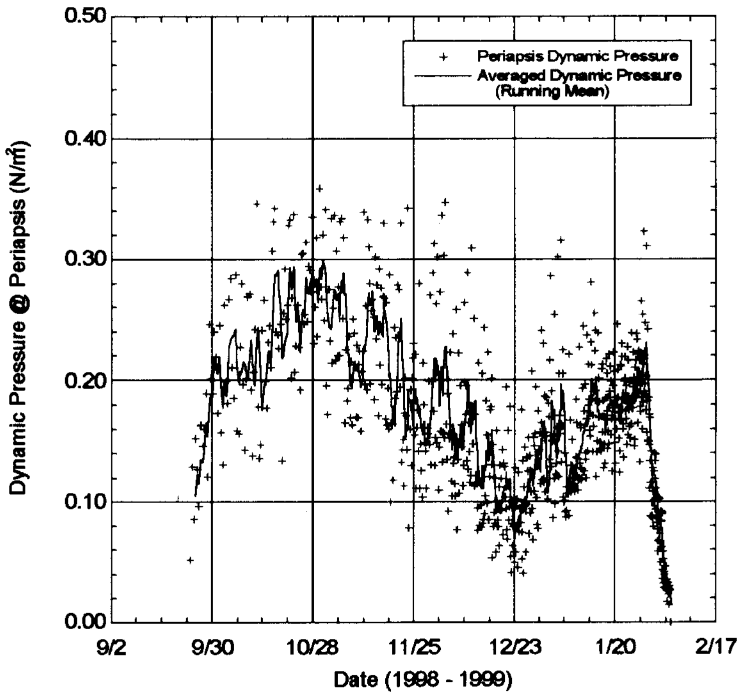

Figure 10 Dynamic Pressure at Periapsis
(Navigation Results: September 1998 - February 1999)

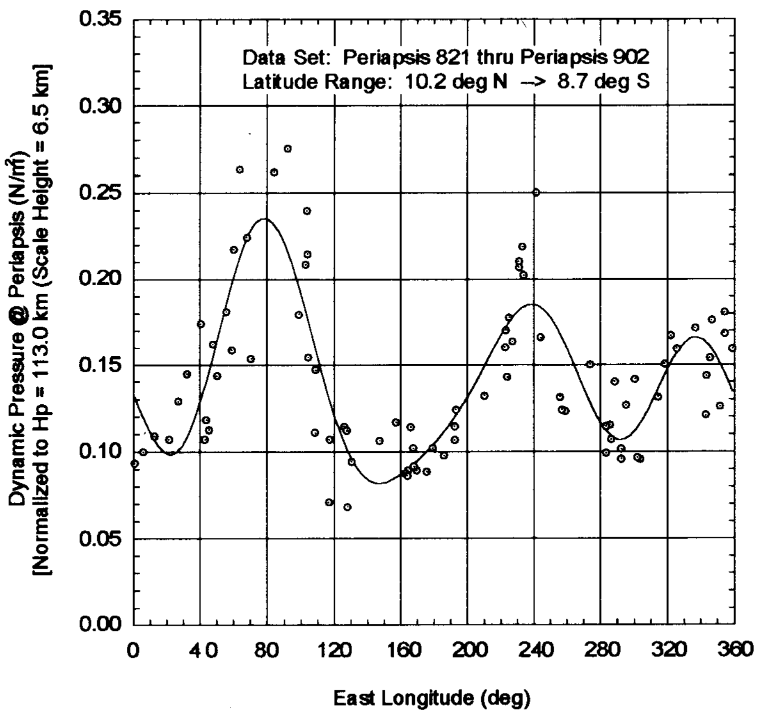

Figure 11 Atmospheric Wave Signature
(Navigation Results: December 1998)

It should be noted that as main phase aerobraking progressed, the atmospheric density field once again exhibited a "wave" pattern that had a strong correlation to longitude. This phenomena was originally observed during Aerobraking Phase 1[12-13]. The signature of this wave pattern is illustrated here in Figure 11 by plotting the normalized periapsis dynamic pressure values versus East longitude. Although the amplitudes of this wave pattern would change during the course of aerobraking, the general location of the relative highs and lows remain unchanged. In order to enhance the trajectory control process by improving the orbit predict capability, this atmospheric wave pattern was incorporated into the Mars-GRAM atmospheric model through the use of regression techniques. These techniques were generally necessary on either a weekly or semiweekly basis.

In Figure 12, the actual orbit period reduction achieved through aerobraking is compared to the planned orbit period reduction of the baseline glide slope. In this figure, the initial aerobraking delay is quite apparent. Additionally this figure shows that the baseline orbit period reduction plan was recovered near the 6.5-hour orbit period mark after seven weeks of aerobraking. From Figure 10, it can be seen that this was achieved by flying the spacecraft at dynamic pressure values that averaged near 0.25 N/m^2. Once the deficit in the orbit period reduction plan was eliminated, dynamic pressure levels were re-set to values that achieved the desired orbit period reduction rate commensurate with the proper LMST progression. It should be noted that the main phase dynamic pressure levels shown in Figure 10 were achieved as periapsis was gradually lowered from initial altitudes near 118 km (at 57 deg North latitude) to final altitudes near 101 km (at 87 deg South latitude).

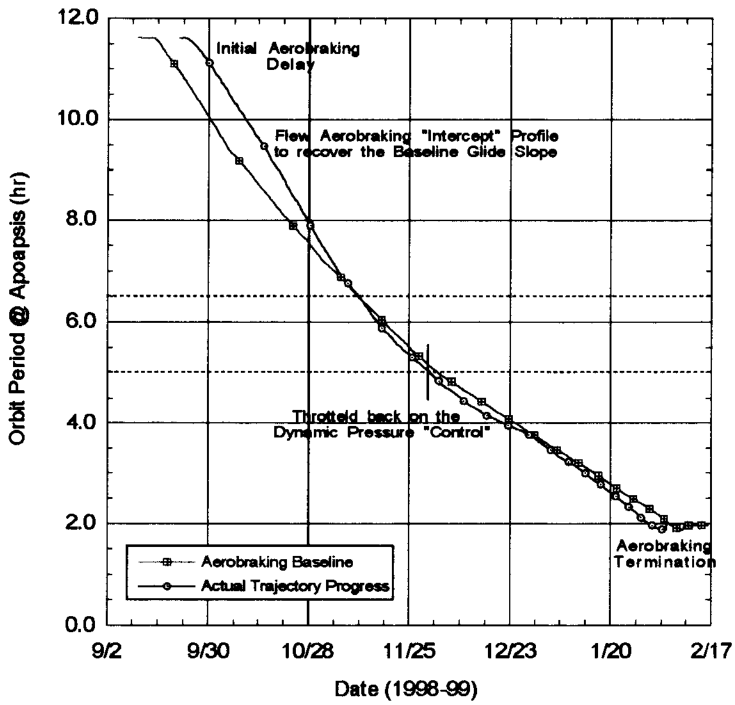

Figure 12 Actual vs Planned Orbit Period Reduction
(Navigation Results: September 1999 - February 1999)

When the orbit period had been reduced to 5 hours, Figure 13 was introduced to monitor the both the orbit period reduction progress and the motion of the descending node toward the 2:00 AM LMST mapping orbit orientation. This figure, which shows both the actual and the baseline apoapsis altitude versus LMST, couples the in-plane orbit period reduction achieved through aerobraking with the planar motion of the descending node of the orbit. As the figure illustrates, as long as the actual orbit period reduction rate maintained the pace of the baseline glide slope, the spacecraft was on target to achieve its proper 2:00 AM LMST mapping orbit orientation. The desired Sun-synchronous mapping orbit condition is illustrated in this figure as the curve becomes vertical near 2:00 AM LMST.

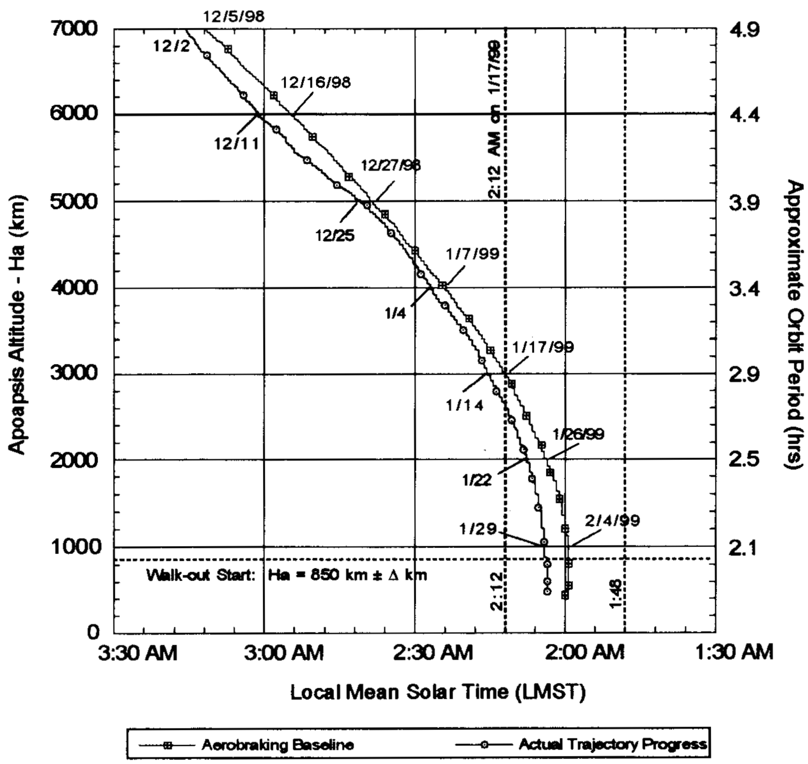

Figure 13 Actual Apoapsis Altitude Decay
(Navigation Results: December 1998 - February 1999)

Aerobraking Walk-out

On January 29, 1999, the aerobraking walk-out phase began and maintenance of the 2-day orbit lifetime went into effect. This final, critical phase of aerobraking was initiated just after the periapsis of the orbit crossed over the South Pole. The actual apoapsis altitude decay history and the location of the four ABMs that were performed in order to maintain the lifetime requirement is shown in Figure 14. This figure also shows the apoapsis altitude decay that was projected in the event any of the ABMs failed to execute. During the walk-out phase, the Mars-GRAM atmospheric model was frequently updated (regressed) in order to match the most current atmospheric observations and thus improve the orbit predict capability. On February 4, 1999, aerobraking was terminated with a propulsive (main engine) maneuver when the apoapsis altitude of the orbit had decayed to a value of 450 km and the descending node had reached a 2:04 AM LMST orientation. The aerobraking termination maneuver raised the periapsis of the orbit to an altitude of 377 km and left the spacecraft in an intermediate "transition" orbit. During this transition orbit, periapsis would naturally reverse it northerly direction over the planet and head back toward the South Pole. Once periapsis reached the South Pole, another main engine maneuver would be performed in order to establish the mapping orbit.

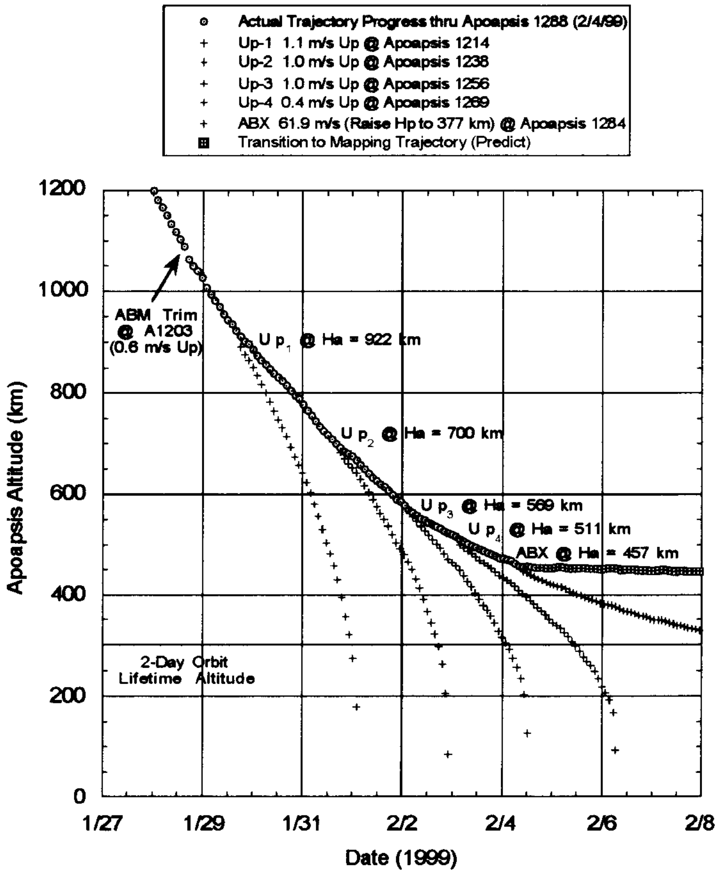

Figure 14 Aerobraking Walk-out Phase
(Navigation Results: January - February 1999)

CONCLUSIONS

After more than 17 months in orbit at Mars, the MGS spacecraft was able to propulsively establish its mapping orbit on February 19, 1999. For the first time, a spacecraft at Mars had successfully employed aerobraking techniques in order to reach its desired mapping orbit. This was accomplished despite a damaged spacecraft solar array. The damaged solar array had forced major revisions to the original aerobraking planning of the MGS mission.

The overall success of the MGS aerobraking experience is best illustrated by Figure 15. This figure shows the total orbit period reduction achieved by the MGS spacecraft during 299 days of aerobraking. During this aerobraking odyssey, the MGS spacecraft performed 891 drag passes, executed 92 trajectory control maneuvers, survived the onset of a Martian dust storm that tripled dynamic pressure values at aerobraking altitudes, and avoided a collision with the Martian moon Phobos as it crossed its orbital path three times. Most importantly, aerobraking had been used to reduce the initial capture orbit period of the spacecraft by more than 43 hours -- a propellant savings of nearly 1250 m/s. With aerobraking completed, the MGS spacecraft was readied for the beginning of its global mapping mission.

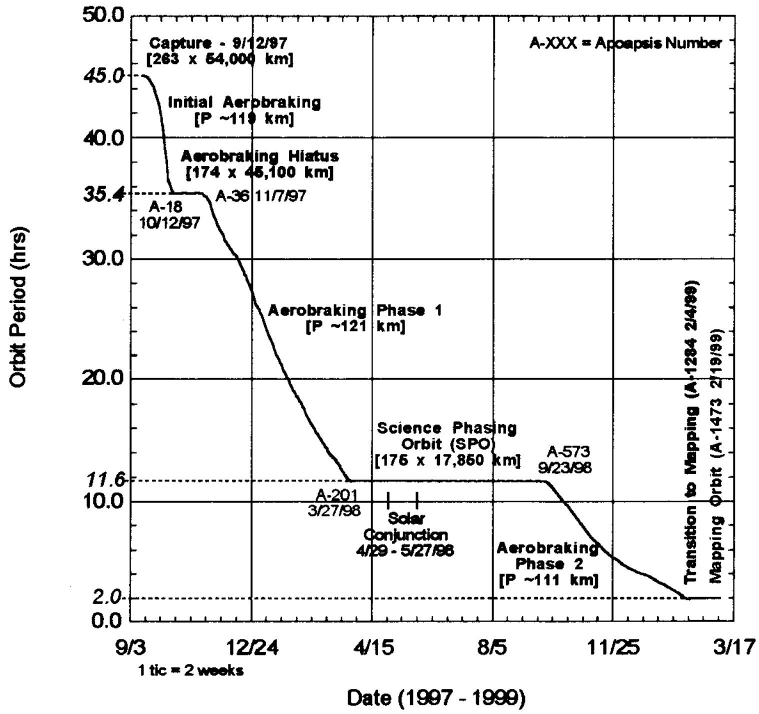

Figure 15 Orbit Period Reduction Achieved By MGS Aerobraking

ACKNOWLEDGMENTS

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